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# Aerospace Research Laboratories

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Contract AF 33(615)-1914
Project 7065



AEROSPACE RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

## FOREWORD

This final technical report was prepared by Aircraft Armaments, Inc., Cockeysville, Maryland, on Contract AF 33(615)-1914, for the Aerospace Research Laboratories, Office of Aerospace Research, United States Air Force. The work reported herein was performed under Project 7065 under the technical cognizance of Lieutenant Richard T. Goddard of the Fluid Dynamics Facilities Laboratory of ARL.

ABSTRACT

The purpose of the present contract was to develop and produce a laser source for the 10 inch schlieren system presently in use at the Fluid Dynamics Facilities Laboratory of ARL. The source, which uses a He-Ne Gas Laser for continuous viewing in conjunction with a Q-switched ruby source for taking very short exposure time photographs, has been developed and incorporated into the existing system. Certain problems still exist which greatly limit the overall system performance, but these are due to factors such as vibration, temperature fluctuations, and the quality of the existing optical system. Recommendations are made for the development of an overall system which will allow the potential of the laser source to be realized.

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## I. INTRODUCTION

This report summarizes the development of both a continuous and a pulsed laser source for use in the Mach 14 Hypersonic Wind Tunnel schlieren instrumentation at ARL. It includes a technical discussion of basic schlieren instruments, their sensitivity, and resolution. Test results, yielded by the integrated equipment, are covered in the following section. Conclusions and recommendations for improvements in the composite system are in Section III. The Appendix includes the procedure for aligning the equipment.

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## II. DISCUSSION

### A. Basic Schlieren Systems

The schlieren system is most commonly used to make visible small spatial fluctuations in the index of refraction of gases. This is accomplished by shining a collimated beam of light through the chamber containing the gas, allowing the fluctuations to cause a deviation of the transmitted light and then processing the transmitted light to remove the deviated light from the image of the test chamber.

The fundamental components of the system are: (a) a small bright source of light, (b) a large-diameter lens or mirror, designated $L_1$, (c) the test chamber, (d) a second large-diameter optical element, designated $L_2$, (e) a knife edge aperture, and (f) a camera. The arrangement of these components is shown schematically in figure 1.

The schlieren system can be considered as two separate optical systems combined. One function is to form an image of the source distribution at the knife edge plane and the other is to form an image of the test section on the film plane. The two functions are intimately related in that the so rce provides the illumination for the test section and the source image at the knife edge allows the modification of the test section image, thus making the density gradients visible.

The source, which we consider to have an arbitrary distribution of brightness, $f(x,y)$* sends light into the first lens L, which collimates this beam, i.e., forms the diverging incident rays into parallel rays. The parallel rays pass through the test section and are focused to a point at the knife edge plane by a second lens, $L_2$. The rays continue past this plane and form an image, either real or virtual, of the test section. The distribution of energy at the knife edge in the absence of any disturbance in the test section, will be the convolution of the source function with the optical system spread function, or:

$$\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x,y)\,s(x-x',y-y')\,dx'dy'.$$

If the size of $f(x,y)$ is much larger than $s(x,y)$, the resulting distribution will resemble $f(x,y)$. If, on the other hand, the converse is true, it will resemble the system spread function, $s(x,y)$. In a good system, the spread function is considerably smaller than the source, thus the source image is quite similar to the source. The spatial points in the source image have no correlation with spatial points in the parallel part of the optical system. The spatial points x and y, measured from the system axis in the knife edge plane, $Z = Z_0$, are homomorphic to the angles of rays with respect to the axis in the test chamber.

Without modification of the transmitted light in the knife edge plane, the optical system will take <u>all</u> rays originating from a point in the test chamber, regardless of the angle they make with the axis, and recombine them in the image. Thus, inhomogeneities which bend the light slightly in the test chamber will not appear dark or light with respect to other points in the test section image. However, it is possible by placing obstacles at certain positions in the plane $Z = Z_0$, say

* We assume here that the variation of flux with angle is small, this being a system specification.

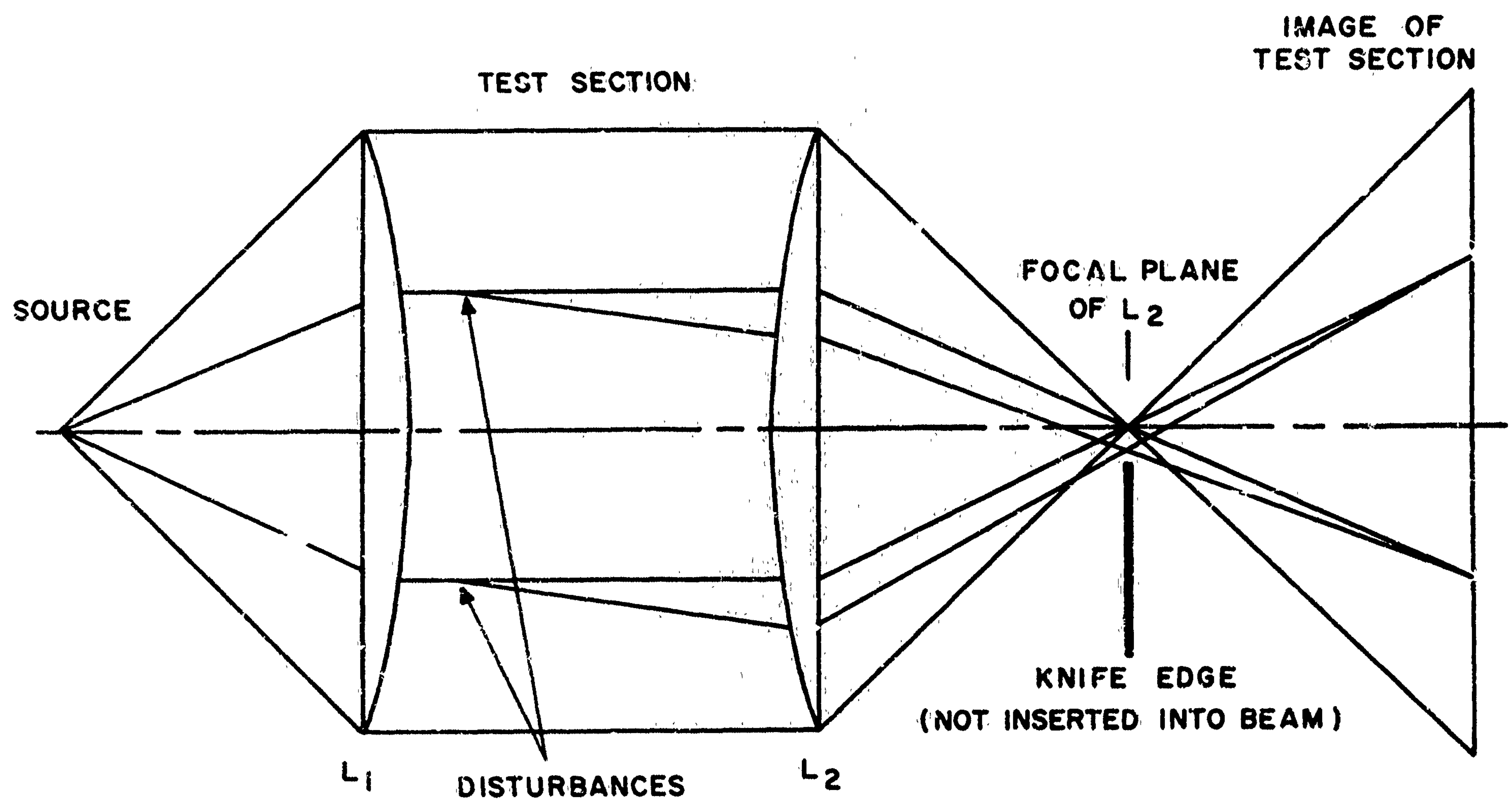



Figure 1. Schematic of Schlieren System

$(x_1,y_1)$ and $(x_2,y_2)$ to remove the light from the transmitted beam which corresponds to angles in the test chamber $(\theta_{x_1},\theta_{y_1})$ and $(\theta_{x_2},\theta_{y_2})$. This causes areas in the test section which have caused the light to be bent at these angles to appear dark in the image of the test section, because this particular light was subtracted from the transmitted light at the plane $Z = Z_o$.

A typical modification of the transmitted light which is performed in operational systems is to insert a knife edge, say a semi-infinite plane with edge parallel to the x axis. Often the knife edge is inserted as close as possible to the middle of the energy distributio under quiescent conditions. This gives an image which is one-half as intense as would be obtained with no knife edge. Then areas in which deflection occurs show up lighter and others darker than the background on the output film. Any disturbance in the test section which deflects some light below the knife edge will appear darker in the final image and conversely any disturbance which deflects light over the knife edge will appear lighter. The entire field should be uniform in the absence of such disturbances. If aberrations are present in the system, no plane can be found for the knife edge, which causes the image to become uniformly dark as the knife edge is advanced into the focused beam. By the same token, the sensitivity is not then uniform over the field. This is a strong argument for a highly corrected system. Relaxation of the requirements on quality may cause the resulting field to be non-uniformly illuminated, with the knife edge inserted under otherwise quiescent conditions.

Discussions of the sensitivity and associated factors center around the energy distribution at the knife edge. The following section touches briefly on this subject.

## B. Schlieren Sensitivity

Collimated light, passing through the test section, is deflected by some spatial fluctuation in the index of refraction. Rays which are deflected to angles $(\theta_x,\theta_y)$ with respect to the axis, all pass through the point $x = \theta_x f$, $y = \theta_y f$, $Z = Z_o$, where $Z_o$ is the focal plane of the lens, $L_2$, in which plane the knife edge is located. The angle that this point makes with respect to the center of the lens, $L_2$, is just $(\theta_x,\theta_y)$. Light which is not deviated in the test section is focused at $x = 0$, $y = 0$, $Z = Z_o$. The important point is that there is a one-to-one correspondence between angles in the test section and points $(x,y)$ in the focal plane.

The source provides the light which is collimated by the lens $L_1$ and subsequently passes through the test chamber. The source has a finite width. The image of this source is centered on the axis of the system at $Z = Z_o$, and subtends a half angle measured from the center of $L_2$ equal to $\theta_o$.

The quasi collimated light which passes through the test chamber is deflected by some spatial fluctuation in the index of refraction. The rays deflected through an angle $(\theta_x,\theta_y)$ cause an image of the source to be centered at $x = \theta_x f$, $y = \theta_y f$, $Z = Z_o$.

A knife edge inserted in $Z = Z_o$ parallel to the x axis blocks all light rays for which $x < 0$, and blocks one-half of the light from an on-axis source in the absence of disturbances in the test section. A disturbance which deflects some light through an angle $(\theta_x, \theta_y)$ causes a second source image to appear at $Z = Z_o$ whose center is shifted to $x = \theta_x f$, $y = \theta_y f$. If $\theta_x$ is positive, the transmitted light is increased, if it is negative, the amount transmitted is reduced. Thus, deflections in the test chamber modify the amount of light transmitted in the system.

The lens $L_2$, in the absence of any modifying diaphragms, takes all light emanating from points $\alpha$ and $\beta$ in the test section, independent of their direction of propagation, and focuses it back to a single image point $(\alpha', \beta')$.

The insertion of the knife edge in the plane $Z = Z_o$ then changes the illumination of the points in the test section image in which deflection from the original propagation direction occurs.

The sensitivity of a given system will be increased if the source, consequently the source image, is reduced in size. The presence of the knife edge causes shifts in the source image to be manifested as changes in intensity of the final image. Thus, a measure of the sensitivity is the half angle, $\theta_o$, subtended by the output spot at the lens, $L_2$, through which the source image must be shifted in order that it be completely eclipsed by the knife edge. Smaller edges have to be shifted correspondingly less than larger images to cause the same amount of illumination in the final image.

The shape of the output spot resembles the shape of the source in most systems, except in cases where the aberrations cause significant distortion in the image. The shape of the source image and knife edge determine the sensitivity function of the system, i.e., the illumination in the final image versus the bending in the test chamber. Generally speaking, the range of the system is proportional to the source image size. Thus, the system sensitivity and range are inversely proportional to one another.

In test facilities where relatively low density flows are used, the spatial fluctuations in density are correspondingly small. In order that these fluctuations be seen, the system must be made more sensitive.

Conventional light sources will only give usable sources down to about a millimeter or so, but energy limitations prevent much improvement on this. The advent of lasers greatly improves the situation because of the tremendous brightness of the laser output. This enables spots as small as 5 microns, with a correspondingly large increase in the sensitivity.

The basic schlieren system is not changed, but the exact nature of the individual components must be carefully examined when laser sources are considered.

C. Resolution of Schlieren Systems

The relation between test section and focal plane is fundamental and bears on both the sensitivity and resolution. It is best discussed using an approach similar to that used by Abbe in analyzing the resolution of a microscope.

Structure in the test chamber is considered to be composed of the sum of a number of spatially periodic gratings by a Fourier synthesis argument in two dimensions. These periodic components are treated as diffraction gratings, which cause a deflection of the light into diffraction orders. Theory of the grating relates the spacing and deflection angles by the simple equation at normal incidence:

$$\sin \theta_i = \frac{n\lambda}{\alpha_i},$$

where $\theta_i$ = the angle for the principle maxima for wavelength $\lambda$ for a grating whose period is $\alpha_i$,

and $n$ = the order of the spectrum.

We require that at least two interference orders pass through the system in order that the corresponding spacing be resolved at the output. In order that this be true, the light in these two orders originating in the test chamber must: (a) pass through the large schlieren element (be it a lens or a mirror), and (b) pass through the aperture located at the knife edge plane. The angles, $\theta$, are typically small, so (a) will normally be satisfied. Rays which are deflected to angles $(\theta_x, \theta_y)$, with respect to the axis, all pass through the knife edge plane at the point $x = \theta_x f$, $y = \theta_y f$, where the knife edge plane is at a distance equal to the focal length of the lens, f. There is a homomorphism between the angles which rays make upon entering the lens and points in the focal plane of the lens. It is this fact on which the schlieren principle works. We desire to determine the relationship between the aperture size at the knife edge and the resolution of the system. Speaking only in terms of one dimension, the relationship between the grating period, $\alpha$, and the location of y of the corresponding order in the knife edge plane, we can relate the two by the following:

$$y = f \sin^{-1} \left(\frac{n\lambda}{\alpha}\right) = f\left(\frac{n\lambda}{\alpha}\right),$$

where the small angle approximation $\theta = \sin \theta$ has been used for simplification, and using the condition previously stated on resolution, i.e., $n = 1$.

$$y = f\left(\frac{\lambda}{\alpha}\right),$$

where $y$ = the distance from the axis in the knife edge plane,

and $\alpha$ = the grating spacing in the test section.

Substituting typical numbers, we have:

$\alpha$ = 1.0 mm,

$f$ = 100 inches,

and $\lambda = 6.3 \times 10^{-5}$ cm.

This gives:

$$y = 100 \frac{6.3 \times 10^{-5} \div 2.54}{10^{-1} \div 2.54} = 6.3 \times 10^{-2} \text{ inches} = 0.063 \text{ inches.}$$

This means that a clear aperture (above the knife edge) of 0.063 inches is necessary in order that sufficient information be available to the camera for it to be able to resolve one-millimeter lines displaced vertically in the test section. A stray light shield (an iris diaphragm) situated near the knife edge, can usually be adjusted to give the required resolution.

Another factor which bears on the resolution of the output is camera motion. If the size reduction from test section to film is five to one, the film must not move more than one-fifth of a millimeter, or about $8 \times 10^{-3}$ inches, during the time of a single exposure. This gives a rough idea of the amount of isolation needed for the camera.

Of course, resolution of density gradients in the gas depends also on the sensitivity of the system, because this determines the contrast in the image which results from a given gradient.

D. System Components

This section discusses the actual components of the laser source which has been developed on this contract. It includes detailed descriptions, reasons for choices, and problems encountered.

1. Laser Source

The term "source" is used in this section to mean all the components necessary to produce the system input spot. In the conventional light source, this is normally a bright Xenon flash lamp or Xenon-Hg lamp, and a lens which collects the lamp energy and focuses it on the input aperture, which is normally a small slit. Because of the relatively large size of these sources, their image is usually larger than the diaphragm, thus the diaphragm itself defines the size of the source. The resulting source spot is the shape of the aperture and is more-or-less uniformly illuminated.

The laser output characteristics are quite different from those above. It is monochromatic and unidirectional. These characteristics allow it to be focused to a very small spot by a highly corrected lens. The spot size thus produced can then be used as the system spot size or source size, since even without any diaphragm at all, it is much smaller than the slit sizes usually used with conventional light sources.

The source developed on the present contract is a combination of two lasers, a He-Ne Gaseous Laser and a Q-switched Ruby Laser. The outputs of the two are combined, using a dichroic mirror, and thereafter pass coincidentally through the system.

The gaseous laser is a Spectra-Physics model 112 laser with a guaranteed output of 8 mw cw power at 6328 Angstroms. It has several features which make it ideal for this application. It has exceptionally good stability, being mounted on a heavy piece of invar tubing. It can be easily pulsed off and on electronically with 100% depth of modulation. It is used to align the optical system, to allow continuous visual monitoring of the picture to be taken, and for taking photographs with moderate exposure times (10 milliseconds).

The pulsed laser was produced by AAI. It consists of a ruby rod in an elliptical cavity, pumped by a Xenon flashlamp. The cavity mirrors are external to the laser rod. Passive Q-switching with a phthalocyanine solution produces output pulses of approximately 30 nanoseconds duration, as shown in figure 7. This pulse is synchronized with the camera to give very short exposures. The laser is designed specifically for this application. Principal considerations were uniformity of output energy, and long life. Pursuant to this first goal, the rod and lamp were water-cooled, and the power supply was engineered to give ±0.25% reproducibility in laser capacitor bank voltage. In addition to water cooling, which increases the system life, the laser is operated at a relatively low level so components (e.g., cavity walls, reflectors) will not deteriorate rapidly.

Both flashlamp and ruby rod are water cooled along their entire bodies. The intercavity reflection losses due to the cooling jackets (vycor) are compensated by the focusing properties of the jackets. Controlling changes in input from the power supply is as important as controlling the temperature of the laser components. The power supply problem is unique in the present case, because of the specified time sequence of shots. A series of 12 shots must be fired at 5-second intervals. This differs from systems which work on a continuously pulsed basis, which are allowed to reach a temperature equilibrium condition after a certain number of shots. Here we must start with a cold system and guarantee uniform output over the first twelve shots. The control of the charging voltage to ±0.25% was achieved as a result of measurements of laser output and its dependence on supply voltage. In addition to the control of the charging cycle, it is also necessary to minimize current leakage from the storage capacitor in the interval between charge cutoff and fire. This is accomplished by: (a) disconnecting all unnecessary circuits from the capacitor bank at charge cutoff, and (b) by placing a triggered spark-gap in series with the water-cooled flashlamp. The latter step was found necessary because the cooling sheath around the flashlamp acts as a resistance in parallel with the lamp, allowing some charge leakage when connected directly to the lamp, even though the lamp manufacturer claims that the coolant is completely isolated from the electrical connection. This was a variable quantity which depended on the condition of the coolant, but was easily measurable.

The charge on the capacitor bank was monitored in these tests by means of a pen recorder in a balanced bridge circuit; the results of these measurements are shown in figures 5 and 6. The instrument impedance was maximized by use of this circuit, but even if some leakage was experienced due to this measurement circuit, it would be constant from firing to firing. Thus, comparisons of relative leakage and charge are still valid. The leakage rate measured by this technique in the final system was 2.8 volts per second at about 2,000 volts. This is a pessimistic measurement, due to the effect of the measurement. Thus, waiting more than about 3.5 seconds between charge cutoff and firing causes a decrease in voltage at firing of 10 volts, which is comparable to the repeatability in the charge cycle.

The physical design of the laser head caused an asymmetrical distribution of fluorescence in the laser rod; the fluorescence tended to be on the flashlamp side of the rod. This is due to: (a) the proximity of the flashlamp and rod, and (b) the focusing sheaths. This resulted in a non-circular laser output spot. This was overcome by placing a 1/8-inch diameter circular aperture in line with the

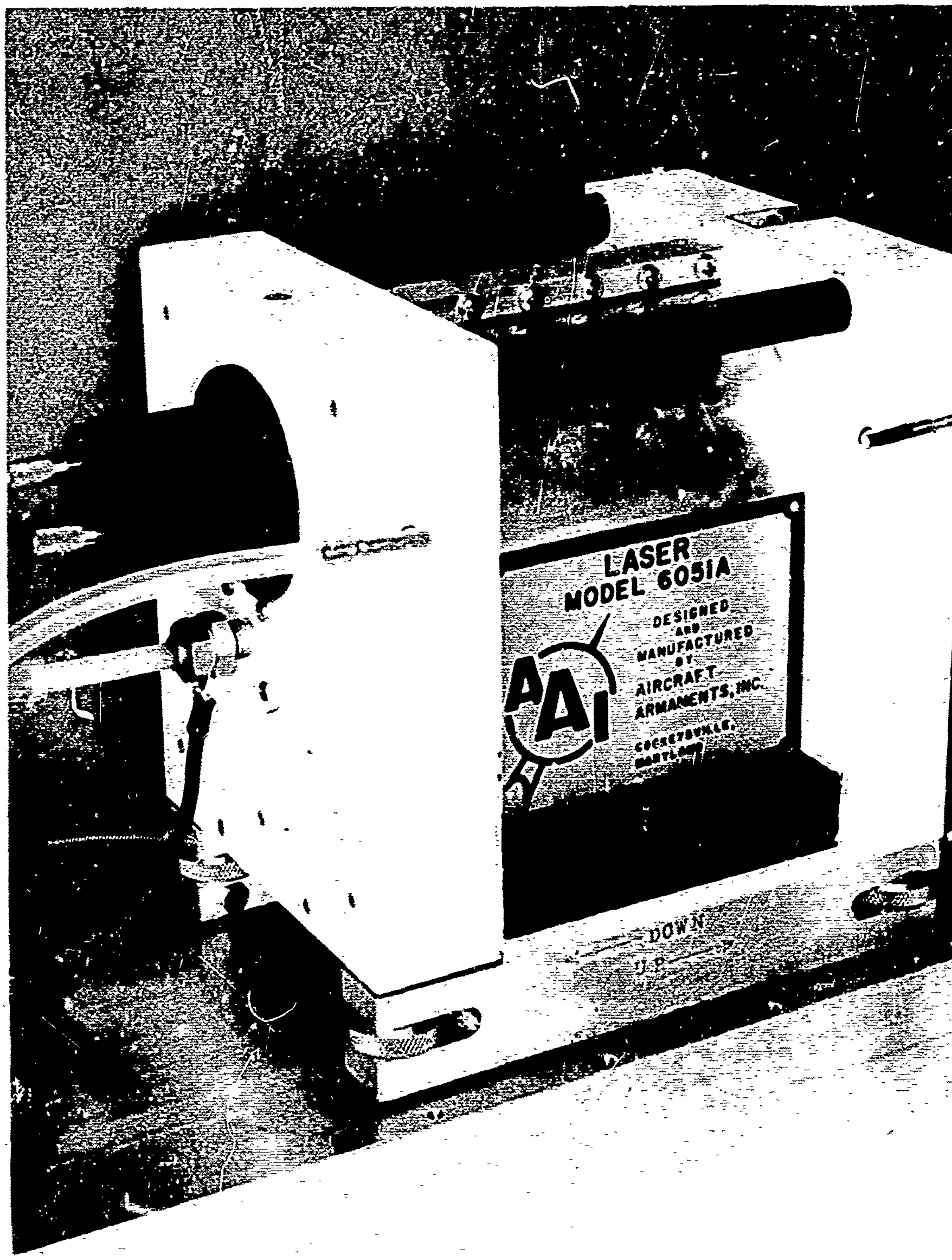



Figure 2. Ruby Laser Head for Schlieren Source

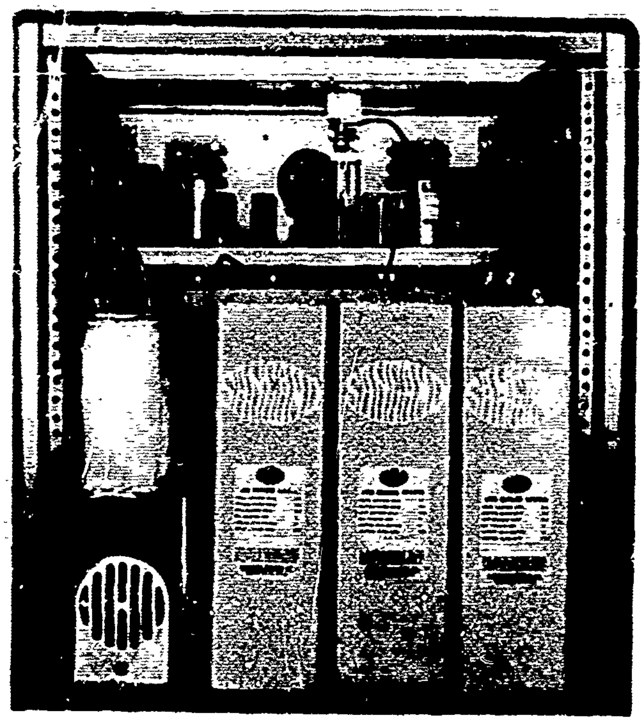


Figure 3. Open Rear View of Laser Power

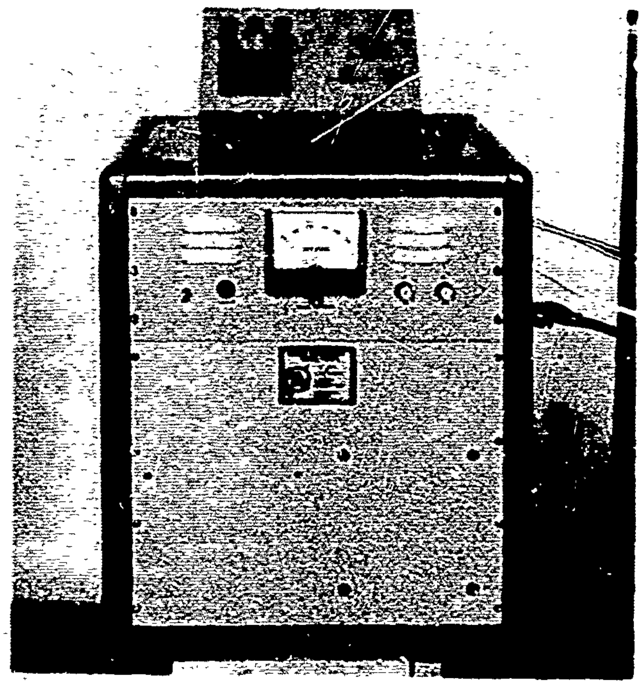


Figure 4. Ruby Laser Power and Control Unit

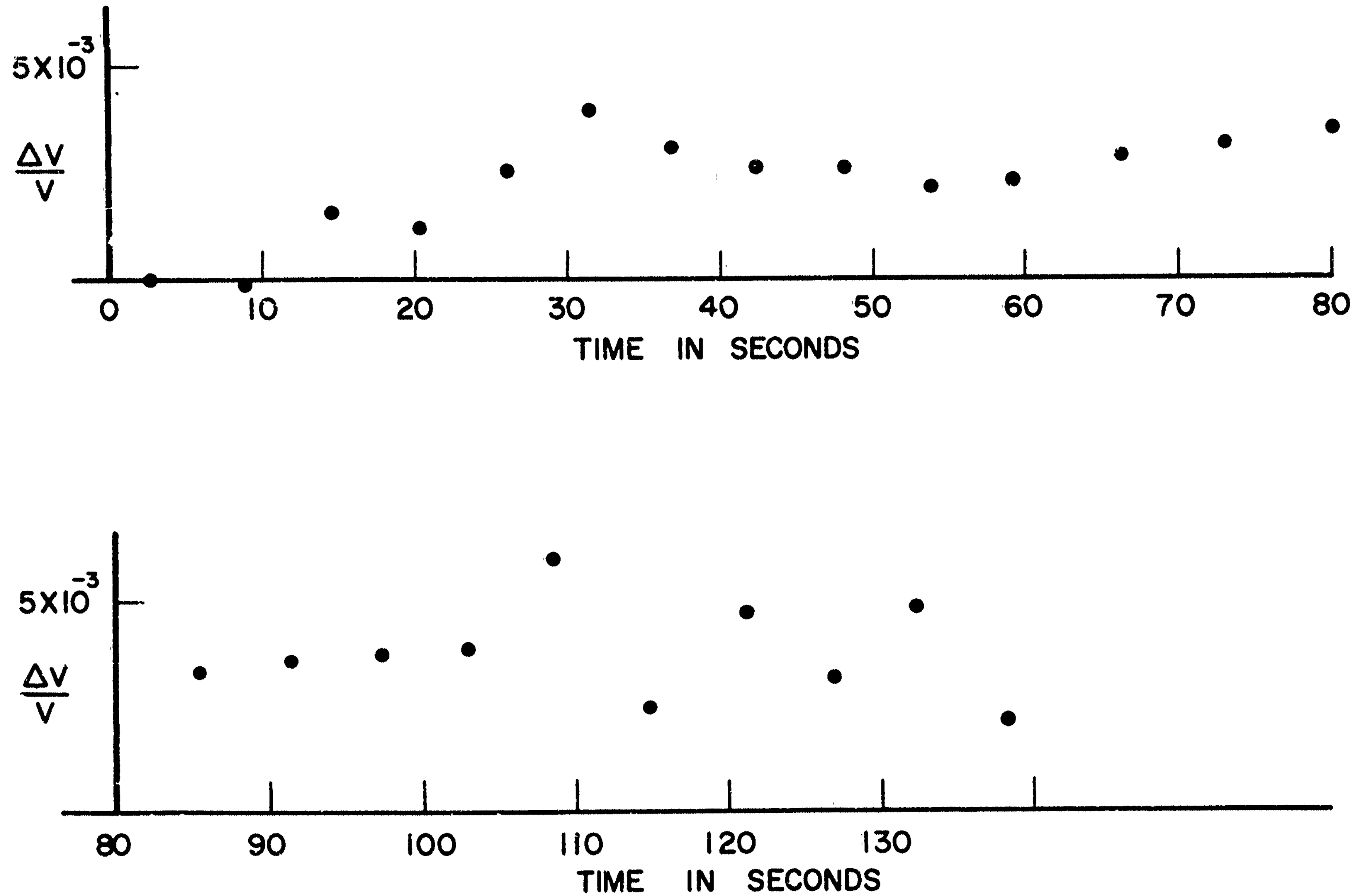



Figure 5. Reproducibility of Voltage on Pulsed Laser Energy Storage Capacitor for Twenty-Four Consecutive Charge-Discharge Cycles

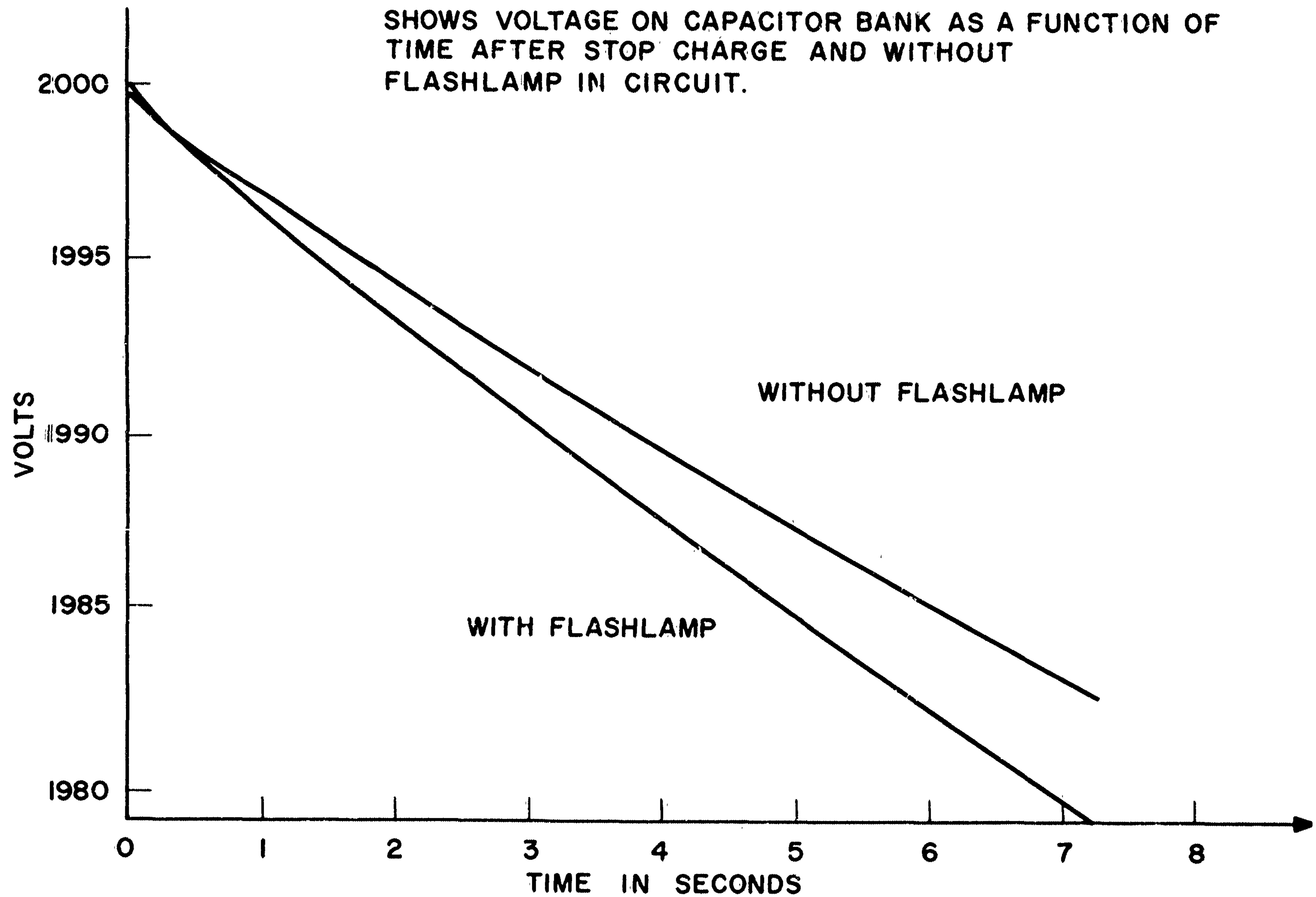



Figure 6. Storage Bank Leakage Rate

rod to discriminate against lasing action around the periphery of the rod and to cause the lasing action to take place in the center of the rod. The laser is made to Q-switch (emit a very short output pulse) by the introduction of phthalocyanine absorber in solution into the cavity. Various path lengths of phthalocyanine solution were tried, from several millimeters up to one inch. This is about a $10^{-6}$ molar solution of a metal phthylocyanine in nitrobenzene sealed in an absorption cell. The threshold for laser action increases relatively slowly with increasing path lengths of this solution. Increasing the input energy above threshold eventually results in more than one output pulse. The range over which a single Q-switch pulse is obtained is quite narrow for the shorter path lengths, but is greater than 200 volts for the one-inch cell. The single and double pulses are illustrated in figures 7 and 8. Thus, the possibility of obtaining more than a single pulse is minimized by the use of the one-inch path length. We have gone farther than requiring merely one pulse output; we are controlling the energy in just one pulse as accurately as possible.

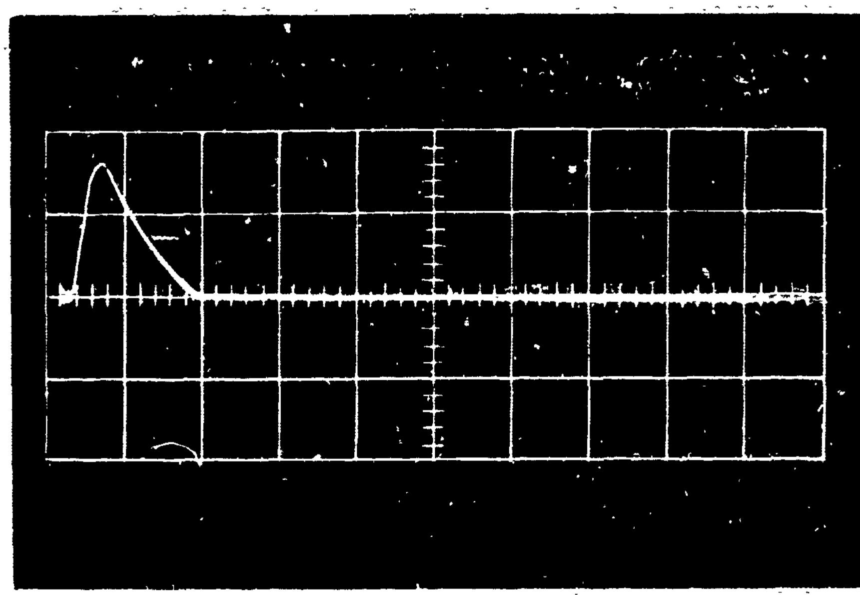
The Q-switch output is not precisely controllable in time, but occurs at some time after the flashlamp is triggered, when the fluorescence has bleached out the absorbing material. If all physical parameters are the same (e.g., temperature, input energy, etc.), one would expect the laser pulses to occur at very nearly the same time. The time reproducibility was investigated and found to be less than 200 microseconds (see figure 9). The exact reproducibility of time is not necessary for the system at hand, because the only requirement is that the laser pulse occur during the time that the mechanical camera shutter is open. The normal synchronization pulse from the camera is used to fire the laser.

These pulses were monitored using a detector with a slow response. It does not show the actual pulse width, but it does show whether one or more pulses occur, and when, because the spacing between pulses is on the order of 100 microseconds. This technique is used because it facilitates scope observation, minimizing delay and synchronization problems.

2. Matching Lens

The nearly parallel beams from the two lasers are focused to a spot which acts as the source for the system. The lens required to do this performs a dual function. It forms the spot, then the beam spreads out so that it illuminates the first large element, $L_1$, evenly. It thereby matches the laser beam to the test section in a sense similar to impedance matching in electronics. The spot size is related to the quality of the laser output and the angle at which the beam spreads out. This is due to a basic law of optics known as the conservation of brightness. The brightness of the beam exiting the laser, and the requirement that this beam illuminate the test chamber with parallel light, along with the f numbers of the matching element and large element, completely determine the source size.

This matching lens must be corrected to form a small spot in space. If the lens contributes spherical aberration, it will be impossible to obtain an even cutoff in the knife edge plane. Color correction improves the agreement of longitudinal position for ruby light (6943 Angstroms) and gas laser output (6328 Angstroms). The difference between these wavelengths is not great, and the relative dispersion of most glasses decreases toward the red end of the spectrum. No difficulties which would indicate a difference in longitudinal position of the two sources have been encountered with the actual system.



Horizontal deflection sensitivity: 50 nanoseconds per CM

Figure 7. High Speed Photograph of Pulsed Laser Output Waveshape

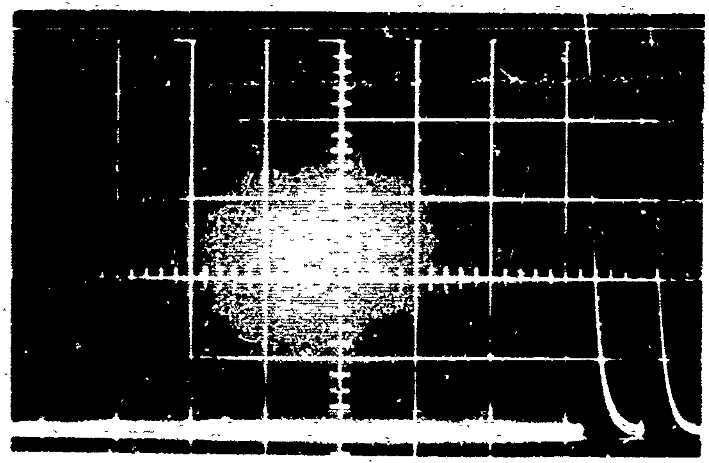


Figure 8. Multiple Pulses in Pulsed Laser Output
(100 Microseconds per CM)

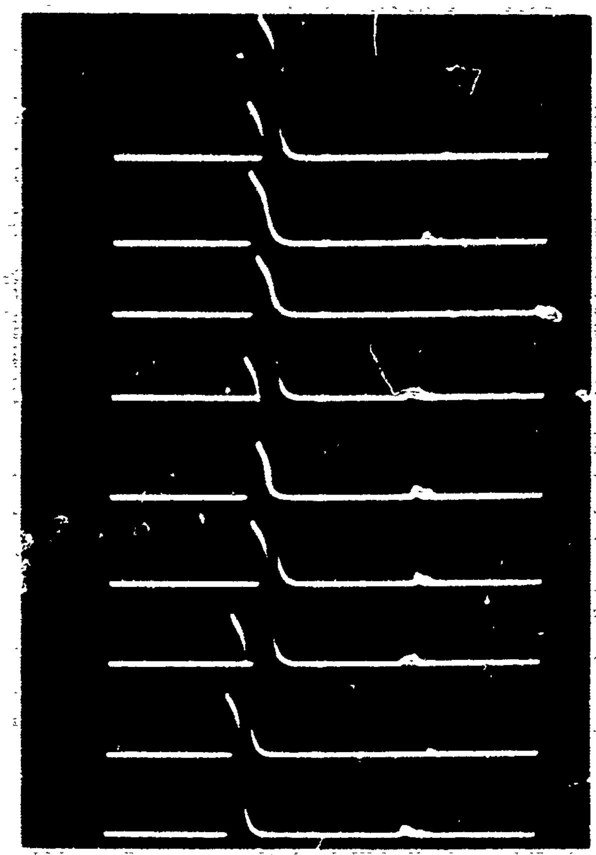


Figure 9. Relative Delay From Firing Time for a Sequence
of Nine Laser Firings at 5 Second Intervals
(200 Microseconds per CM)

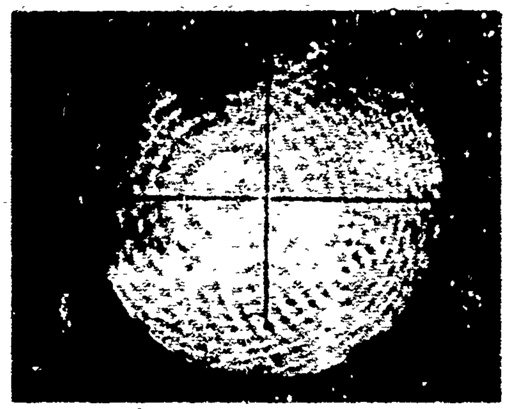
A ten-power microscope objective has been found ideal for this lens. It is well corrected, has a reasonable working distance, and affords a good compromise between efficient use of energy and uniformity of illumination of the test chamber. From a mechanical point of view, the readily available mounts and adjustments for such elements make them quite attractive. These lens are coated with standard anti-reflection coatings, which suffice, especially since the position of this element reduces the effects of reflected light from it.

The source size formed by the lens using the gas laser is estimated to be approximately 7.5 microns. This is based on the diffraction-limited spot size, which is a reasonable assumption because of the quality of both the microscope objective and the gas laser output.

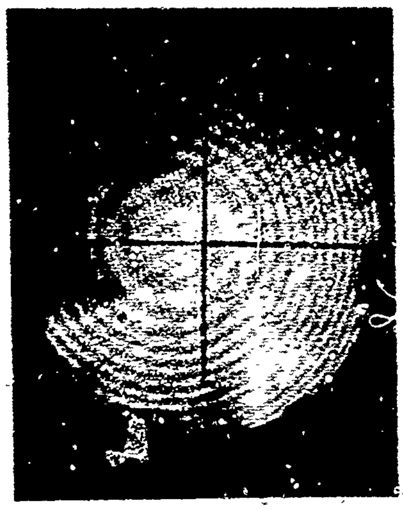
The source size formed by the lens using the ruby laser light is not this good, but is less than 0.004 inch. These sizes are difficult to measure exactly in the existing optical system for reasons which will be examined later. The upper limit on the ruby laser spot was measured by placing a piece of metal at the focus of the microscope objective and examining the diameter of the crater produced by the ruby laser. A small circular source aperture is placed at the source location. The aperture is not necessarily used to define the source, but performs a spatial filtering function, eliminating structure which would be introduced into the source output due to reflections, dust, or bubbles in the elements which preceded the aperture. This function is illustrated in figure 10. Adjustments between the lasers, the lens and the aperture are provided. The source point must be located exactly at the focal point of the collimating element. This aperture is a diamond wire-drawing die, which was chosen because it stands up well under the bombardment of this ruby laser. The laser burned holes in thin metal diaphragms which were tried. The diamond die has actually a small clear aperture in the center and, when viewed normally (as used), an annular transparent region can also be seen. This is due to a light path through the crystal, but is far enough from the central aperture that it is not harmful. Care must be exercised in the initial alignment to insure the beam is passing through the proper aperture.

3. Beam Splitter

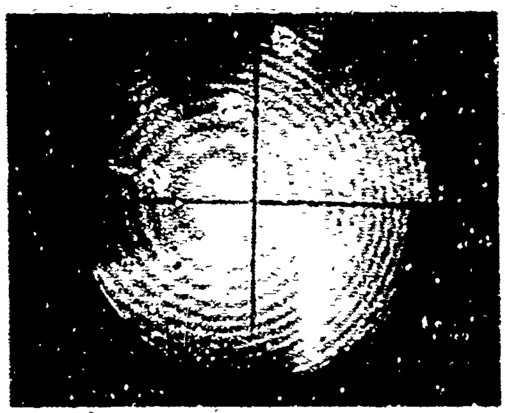
The double-pass nature of the system, originally used for increasing the sensitivity, only complicates the laser system, since the inherent sensitivity is more than sufficient. This configuration requires a system in which the input and output are coincident. This, in turn, requires a device for separation of these beams. The conventional method is with a beam splitter. Several types of beam splitters were investigated on this contract. The three basic types are: (a) a flat piece of glass with parallel faces and reflection coatings, (b) the thin film type, and (c) the prism type. All of these have disadvantages. The glass plate with a partially reflecting coating at $45^{\circ}$ incidence, although it has been successfully used in many conventional systems, causes astigmatism in the transmitted beam. This was not noticeable in this system with a conventional source because of the relatively large size of the source. With the laser source, the resulting astigmatism is intolerable with plates of reasonable thickness. The thin film type is similar except this substrate is extremely thin, thus astigmatism is not the problem. Strong interference effects do occur due to reflections off front and back. These can be minimized by anti-reflection coatings on the rear surface. These films, however, cannot maintain flatness of one-tenth of a wavelength and, although they do take simple coatings, multiple coatings tend to craze. On the basis of these considerations, the thin film beam splitter was also rejected. The prism beam splitter is



Field illumination without filtering
source aperture



Field illumination with a 0.005 inch
aperture



Field illumination with a 0.001 inch
aperture

Figure 10. Effect of Source Apertures on Field Illumination (Gas Laser)

made by cementing two right angle prisms together on their hypotenuse face, after putting a partially reflecting coating on one such face. The resulting prism is cubical in shape; the beams enter normal to the faces of the prism, which are anti-reflection coated. The use at normal incidence eliminates the astigmatism, but some problems still exist due to unwanted reflections from the face of the prism. These occur in spite of the anti-reflection coatings on these faces. After much puzzling, a solution was eventually worked out. This scheme involves the use of the polarization of the laser output.

Linear polarization of the outputs of both lasers is guaranteed by placing of the Glan Thompson prism in front of the microscope objective. A quarter wave plate is placed between the beam splitter and the large spherical mirror. A second Glan Thompson prism is placed between the knife edge plane and the camera. At the knife edge the reflections from the faces of the prism beam splitter have a polarization perpendicular to that which passes through the entire system. The last Glan Thompson prism rejects the unwanted reflections and passes the rest of the light. Interference between the reflections from the faces of the beam splitter prism still cause some modulation of the transmitted light, even though they are coated. This shows up as very faint linear fringes across the field under gas laser illumination.

4. Existing Optical System

The present optical system, which is the property of ARL, consists of a sealed and **evacuated** collimator tube, and an external plane mirror to redirect the light which exits the tube through a large window, back into the collimator tube. The double-pass system is essentially the system shown in figure 1, folded onto itself by the plane mirror so a single spherical mirror performs the function of $L_1$ and $L_2$. The collimator contains, in the order they are encountered in the system: an entrace window, a front-surfaced mirror, a corrector lens, a 10-inch diameter spherical mirror, and window. This is illustrated in figure 11. The large off-axis angle requires some correction of the resulting astigmatism; this is the purpose of the corrector lens. The correction was sufficient when used with a conventional light source because the source size was relatively large.

As a result of work with this system using the gas laser source, the degree of correction of the system has been obvious. The optics are completely unable to reproduce the gas laser source spot at the knife edge and only produce an output which is characteristic of the optical system itself. Any input less than 4 mils is reproduced as a 4-mil spot at the output.

Historically, it is interesting to see how this kind of optical system evolved in this form. Up to the advent of the laser, powerful white light sources have been used in these systems. Thus, the relatively large amount of chromatic aberration (distance) associated with large-diameter optics would have caused the various color components to focus at different positions along the axis and to pass through the test chamber at different angles. The use of mirrors eliminates this problem, but introduces others. Mirror systems characteristically have the center of the field obscured. This is not desirable in schlieren systems, since the test chamber is in the near field of the collimator. Using de-centered or off-axis systems gets around the obscuration problem, but introduces bad aberrations. The aberrations are bothersome, but most users have learned to live with them. Also, since the white light sources are relatively large, sensitivity to aberrations is not so great as when a small source is to be imaged by the optical system.

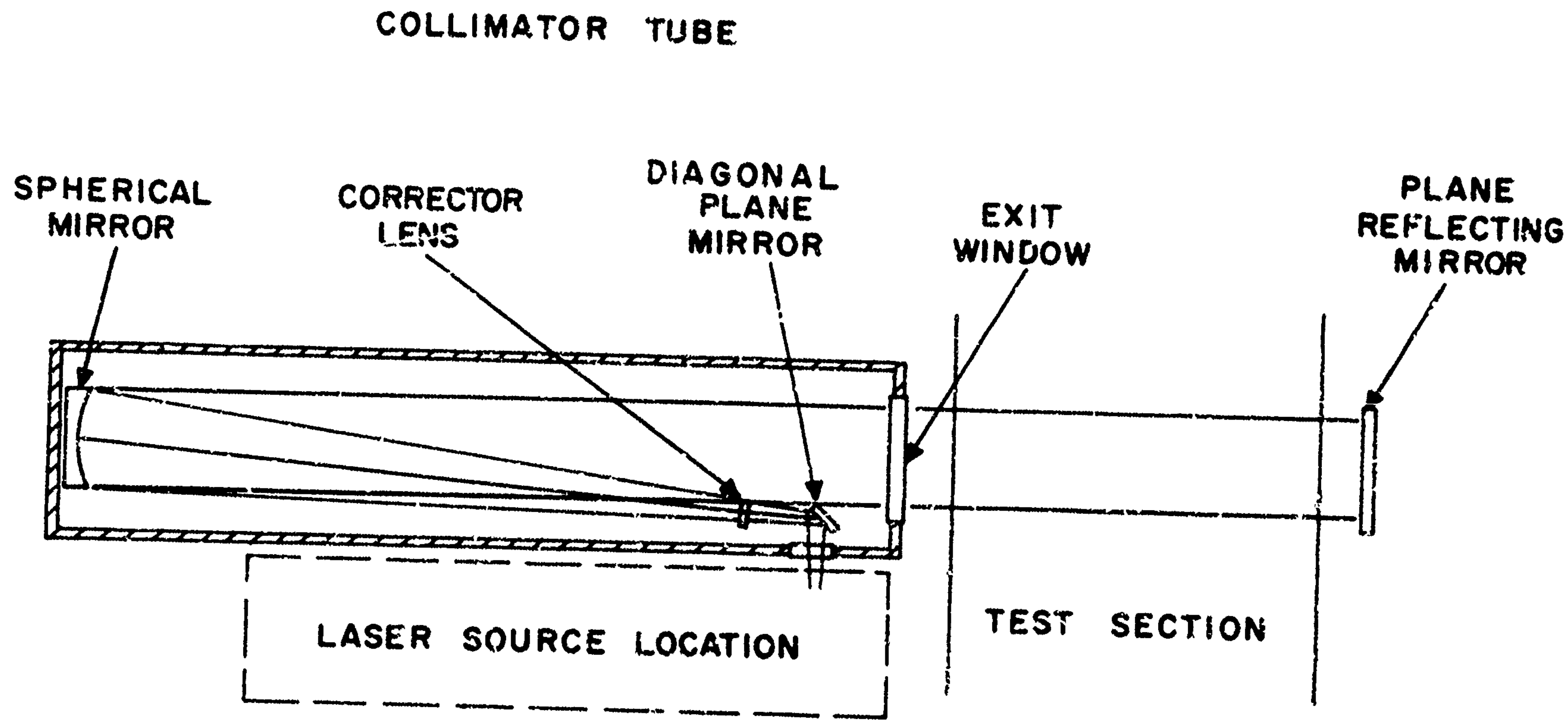



Figure 11. Schematic of ARL Optical System

The laser source has been mounted on this optical system and aligned with it, the source point being made to coincide with the focal point of the large mirror. When the external plane mirror is properly positioned, the exiting beam is superimposed on the entering beam back to the beam splitter which separates the two.

The beam comes to a focus at the plane of the knife edge, forming an image of the source.

5. Knife Edge

The knife edge and its adjustments are required to move smoothly and reproducibly through extremely small distances, i.e., $10^{-4}$ inches. The total range of motion required is not large. This has been accomplished by the use of a simple parallelogram flexure, which provides the required translation of the knife edge. The drivers are commercial micrometer drives with large barrels which read directly to 0.0001 inch. The knife edge can be adjusted about the axis of the system. An aperture near the knife edge plane limits stray light transmission and acts as the aperture stop for the system. The relationship between system resolution and theory of schlieren systems hinge on the energy distribution in this plane, the knife edge position and shape, and the size of the limiting aperture. These are discussed in an earlier section.

As mentioned previously, a Glan Thompson prism is mounted just outside the knife edge plane for the purpose of eliminating the unwanted reflections from the beam splitter.

6.. Camera

The camera is a 35 mm Leica with a long focal length lens, extension bellows, and rack and pinion mount. It incorporates a reflex housing for viewing the image on a ground glass screen. The sync output from the camera is used to fire the pulsed laser. The gas laser is electronically pulsed off during the time the shutter is open. The film chosen for this work is Eastman Kodak Linograph Shellburst, which has a good red sensitivity where most panchromatic emulsions have absolutely no response. It is a fine-grained film of moderate sensitivity and readily available. It must be processed in absolute darkness because of its red sensitivity, but other than this, it is easily worked with, developed ideally for 8 minutes in D-76 at $68^{\circ}$ F.

The energy available from the pulsed laser for taking the photograph is adjusted by a special prism situated directly in front of the pulsed laser. If photographs are to be made using the gas laser, the energy is best varied by the plate current adjustment on the gas laser power supply.

7. The Mounting Platform

The platform on which the laser source is mounted rests by means of a three-point suspension on a rigid bracket built out from the side of the collimator. The three knurled knobs at the ends of the platform translate the platform vertically and change its angular orientation with respect to the collimator tube, the whole purpose being to put the laser source spot at the focal point of the large spherical element within the tube. These adjustments are provided with locks to aid in maintaining alignment.

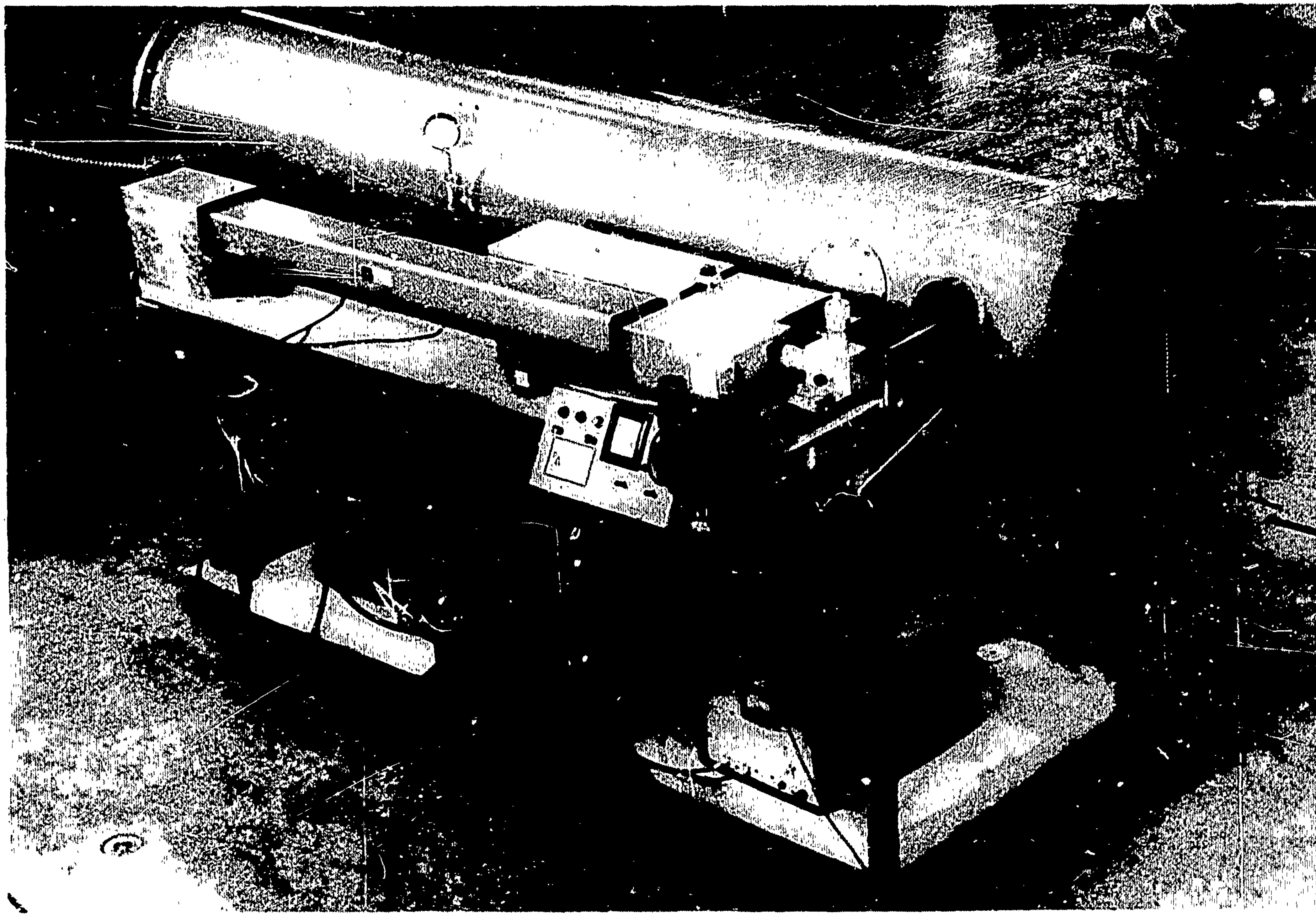


Figure 12. Laser Sources Mounted on the Collimating Tube at Aerospace Research Laboratories

## E. Fabrication of the System

The first phase of the contract was directed toward the design of the overall system, components, and hardware. The procurement of specified optics is a long, slow process. A subsequent delay in system testing was anticipated. To minimize the dependence of the contractual delivery date on this lengthy procurement, some additional components were simultaneously ordered in cases where alternatives in the system design were to be evaluated against the chosen concept.

A test rig, consisting of a 5-inch lens and plane mirror, were fabricated to simulate that part of the overall system which existed at ARL. When the system was ultimately fabricated and ready for testing, the test rig (in particular, the lens) was found not to have the needed quality for complete testing. This arrangement did allow familiarization with the optical system, development of techniques for alignment, and direct encounter with some heretofore only suspected difficulties.

Paralleling the fabrication of the optical components, the development of the pulsed ruby laser was carried out. There were to be several features unique to this laser which would require careful laboratory development and testing. These were cooling, Q-switching, and energy control. Temperature of the ruby rod and the incident energy were factors which governed the output. This light output was specified to be repeatable at the repetition rate of 12 pulses per minute. Temperature change was to be held to a minimum by passing distilled water around the rod under positive pressure. The same coolant was used for the flash lamp to stabilize its output and extend the lamp life. Some problems with fittings and seals occurred initially, but subsequent modifications corrected this. One later breakdown was attributed to repeated firing of the laser without operating the coolant pump. Presumably, a vapor pressure build-up broke the seal. Final design now includes automatic and continuous pump energization when the laser power unit is on.

Electronic control of the energy input was accomplished by a two-stage feedback circuit which could accurately sense the storage bank charging voltage. The feedback circuit operates from a 200-volt regulated supply.

Short pulse duration, accomplished by Q-switching, is performed passively with a vanadium-phthalocyanine liquid bleachable filter. The effects of various cell-path lengths and energy inputs were studied. The design which eventually became firm is described in a previous section.

The laser system was thoroughly tested and is now considered quite reliable. No sign of laser mirror deterioration was observed after the laser was fired about a thousand times. This is at least partially attributable to the fact that the cavity, when assembled, is dust-tight. Once the laser is closed up, no additional dust can enter the cavity and stick to the mirror.

Although the substitute optical system used for test purposes was not of the necessary quality, it did allow us to grasp some of the overall systems problems, while it was at AAI, such as beam splitter comparisons, elimination of unwanted reflections, and other adjustment modifications.

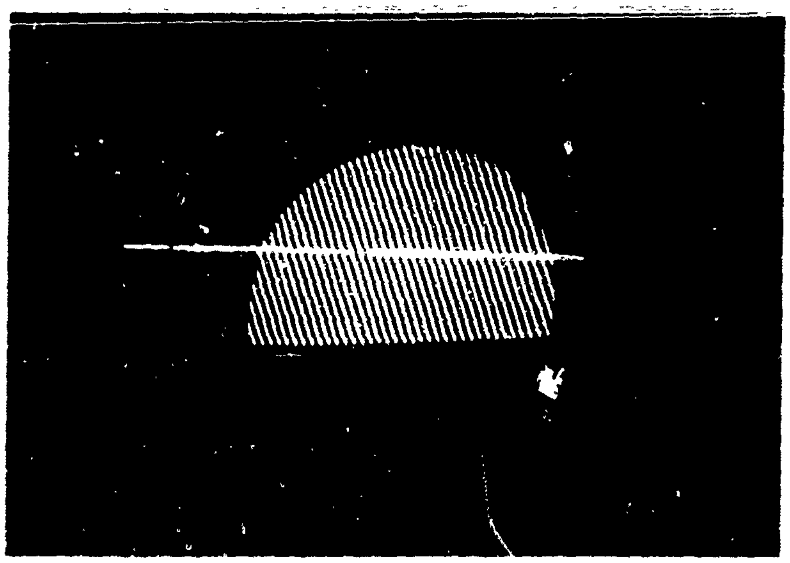
The equipment was shipped from AAI to ARL on January 4, 1965. The first week was spent in transporting, reassembling and mounting the equipment on the existing collimator tube at ARL. The system was initially set up without the tunnel test section interposed so the work could be carried on without preventing normal use of the tunnel.

The first observations of the test section image quality indicated several problems. First, the unwanted reflections from the surfaces of the prism beam splitter were more prominent than at AAI because of the greater losses in the schlieren optics at ARL. The polarization-separation scheme was conceived and implemented. The success of this method is illustrated in figure 13. Second, quite prominent concentric rings could be seen superimposed on the test chamber image. No adjustments of the exterior optics could influence these rings and their position with respect to the system cross-hairs which are engraved on the spherical mirror. Third, no plane could be located for the knife edge which would give a good cutoff, e. g., that would give an even illumination of the field, with the knife edge inserted. Fourth, the image could be seen to flicker at a frequency of several cycles per second. The environment was also a poor one from the viewpoint of thermal fluctuations; large blowers and the opening of doors caused strong drafts on the equipment.

A helpful technique was developed for alignment and studying of system quality and performance. It utilizes a microscope objective to focus the knife edge plane onto the camera viewing screen. This makes the knife edge and source image easily visible. Observations then indicated several problems. One difficulty was the effect of the floor vibrations on the optical system. This caused a flickering of the image. These were transmitted from the concrete floor directly to the rigid steel frame on which the equipment is mounted. Several expedient schemes were attempted to reduce this vibration. One, utilizing large foam plastic pads, did not work out. The vibration was eventually reduced to a reasonable level by the installation of a shock mount under each leg. The height of the optical centerline was increased by these mounts, causing misalignment with the windows on the tunnel.

In order to determine the frequencies characterizing the remaining system vibrations, a photodetector was placed in the film plane of the camera and the output connected to an oscilloscope. The fluctuations in the output signal with the knife edge inserted were measured. The principal frequencies were determined to be about 16 cps, with a modulating beat-frequency of 1.5 cps. These measurements were not made with the system in place on the tunnel, and are not to be used in the design of any subsequent vibration isolation studies. They do indicate the feasibility of the measurement technique and give a rough idea of the frequencies to be encountered in this general area.

Observation of the gas laser source image, viewed in the knife edge plane, showed an image greatly distorted from the effective source at the entrance aperture. The optical system in the collimating tube had large aberrations (relative to use with the laser source). Although a correction element is incorporated, it was found to be acceptable only when this system used the conventional light source. Since the gas laser source size is so much smaller than the conventional source, it would require a more nearly perfect optical system to form a good image of it. The astigmatism and the asymetrical circle of least confusion of the laser source image are illustrated in figure 14. The principal result of this to the user is a non-uniform distribution of light over the test section image when the knife edge is inserted (figure 15). This implies a non-uniform sensitivity over the field. The limiting image size which the system can reproduce is about $4 \times 10^{-3}$ inches in diameter. This is the measured diameter of the system output spot.



Interference fringes in unwanted reflections from surfaces of the prism beam splitter. (Return from the test chamber has been blocked in order that the reflections be seen more clearly.)

Elimination of these fringes with the incorporation of polarizing prisms and quarter-wave plate.

Figure 13. Elimination of Unwanted Beam Splitter Reflections

$\Delta L = -.050$ inches

$\Delta L = -0.025$ inches

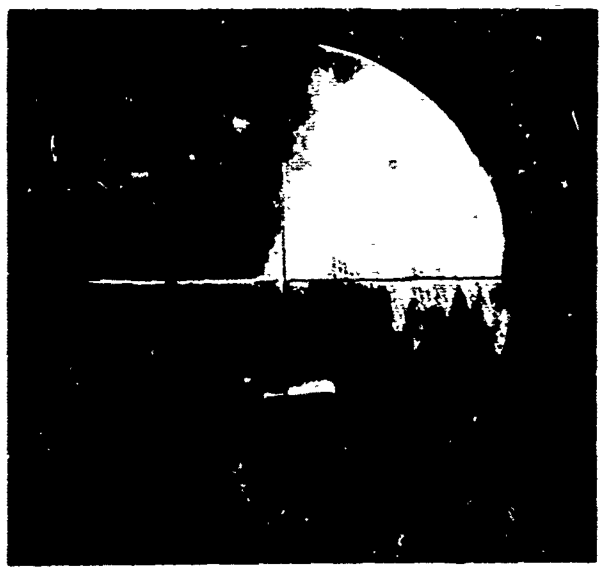
$\Delta L = 0.000$ inches

$\Delta L = 0.025$ inches

$\Delta L = 0.050$ inches

$\Delta L = L_o$ where $L_o$ is the optimum longitudinal knife edge setting

Figure 14. Astigmatism of Present Optical System Image of Gas Laser Source at Various Longitudinal Positions Near the Focal Plane



Illumination by the Gas Laser shows characteristic non-uniformity due to imperfections in the optical system. Object visible in lower center is top of flashlight pointed upward.

Figure 15. Illumination by the Gas Laser Showing Non-Uniformity

The interference rings observed in the camera image plane are due to reflections from the front and rear surfaces of the collimator window. Interference between the light reflected from these surfaces is enhanced by the coherence of the gas laser light. However, this reflected pattern is not what is seen in the image plane, because the window is deliberately cocked at an angle with respect to the system axis. It is the absence of this light (which is subtracted from the transmitted beam) that causes a visible interference pattern in the image plane. Proper coating of this window will greatly reduce this pattern. The ring structure can be clearly seen in figure 10.

In order to check the spot size measurement, which (along with the focal length of the output element) determines the sensitivity, some photographs were taken with a variable standard schlieren (figure 16). No densitometer measurement of these photographs are available, but with all the imperfections, such as rings and non-uniform field illumination, the value of such quantitative calculations is questionable. They do serve to give a good estimate of system sensitivity. The measured sensitivity checks with the output spot size.

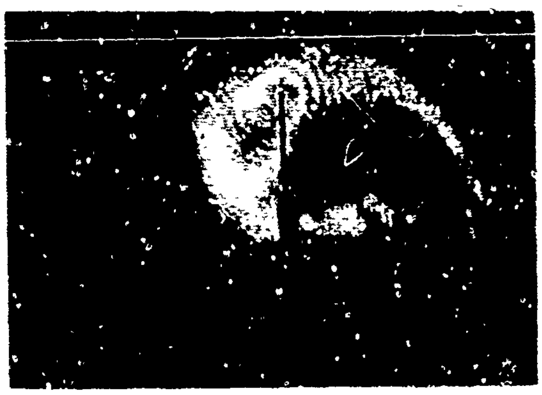
The effect of ambient temperature fluctuations on the performance of the system, other than the inhomogeneities in the light path, was noted principally by the fact that the knife edge setting would drift relative to the source image. That is, in a period of ten minutes or so, the knife edge setting was significantly changed ($10^{-3}$ inches). This is attributed to changes in dimension due to small changes in ambient temperature. Thus, considerations of systems with increased sensitivity must include these temperature effects.

Photographs taken with the gas laser exhibit a structure which is not observed when the system is viewed through the reflex housing. It is a five-sided pattern with roughly radial bright lines. This is because the leaf type shutter used for these relatively long exposures is not in the objective plane of the system. Thus, positions in the shutter plane are correlated with positions in the image plane. Since all points in the shutter plane are not exposed for equal times, the photographs are not uniformly exposed. This effect can be clearly seen in figure 10.

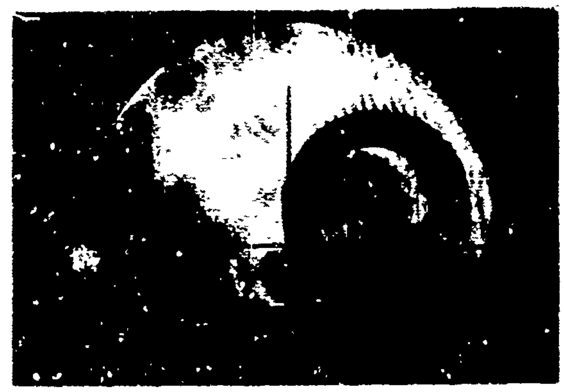
Generally speaking, the gas laser is a very critical tool with which an optical system can be studied, but in some instances its extreme sensitivity causes effects which are not desirable. The high quality of the laser output does offer promise for a much more sensitive system, but this brings with it much more stringent requirements from the standpoint of environmental factors and optical quality.

After making observations of the above phenomena using the gas laser, the Q-switched ruby laser was installed and initial attempts were made to align it with the optical system. Initially, the installation and adjustment was carried on in the laboratory where the tunnel, on which it was to be installed, was located. The severity of the environment was noted, but since the equipment was to operate in this environment, it seemed that the initial alignment might as well be performed there. Initial difficulties in aligning this laser caused a reconsideration of this policy; at the beginning of the fourth week the equipment was moved into a better environment, where the adjustment procedures were much more easily performed.

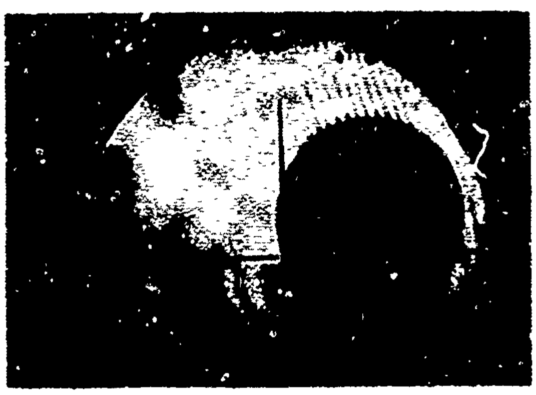
The technique worked out at AAI for the purpose of aligning this laser with the rest of the system did not work because of the greater losses in the ARL



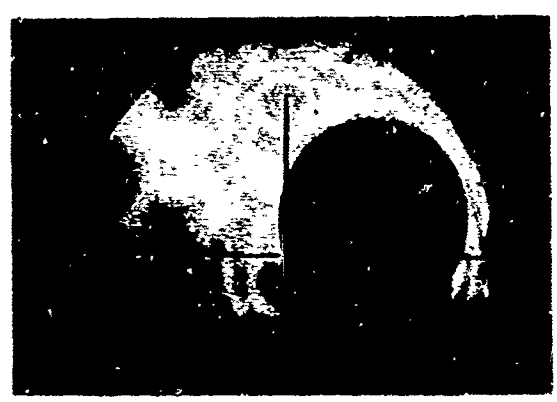
0 arc-seconds



1 arc-second



2 arc-seconds



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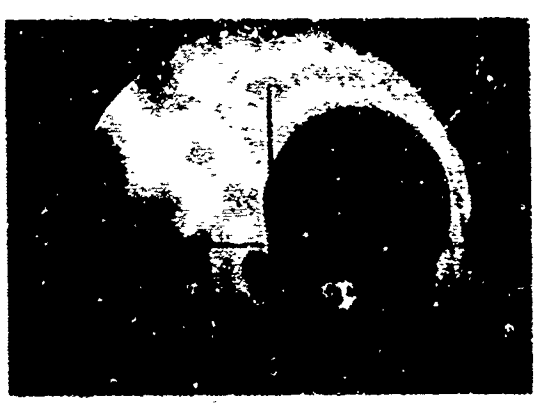


4 seconds of arc

Figure 16. Schlieren System Photographs of Standard Schlieren Rotated to Give the Designated Deviations

system. Another technique, which required only the addition of a small mirror with an adjustable mount, was devised. The alignment procedure is discussed in the appendix. After some additional modifications to the adjustment system, the ruby laser was aligned without undue difficulty.

Initial photographs indicated that additional shielding of the camera from the laser pump light was necessary. This light was leaking through the plastic end pieces on the laser head. Additional felt masking of the outer laser head cover solved this problem.

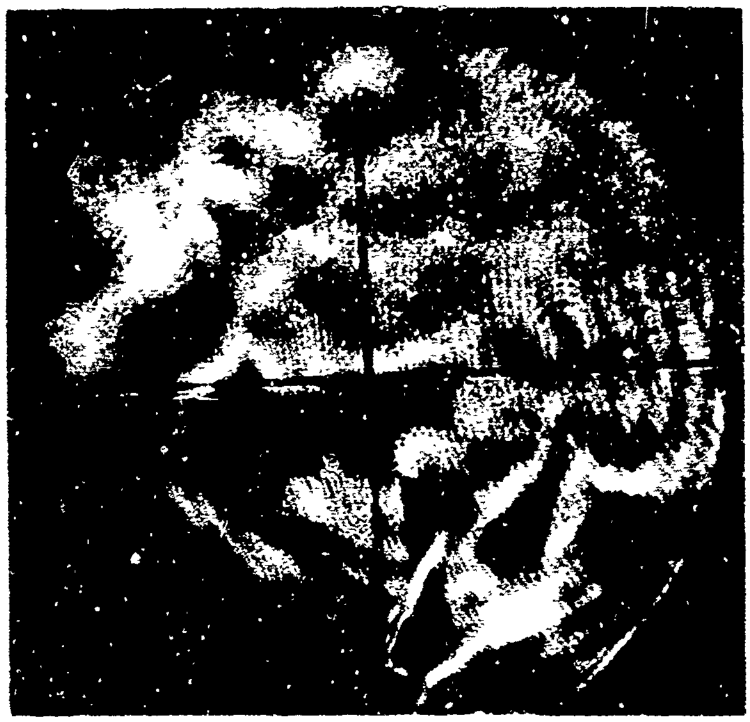
A series of photographs was then taken to determine the proper setting of the laser attenuator for the system. This attenuator was then set at what was considered the optimum value, and several other runs were made (figure 17).

One of the most interesting results of these photographs was that, in contrast to the gas laser photographs, the rings due to interference were almost completely absent. Another fact that was noted was that the system knife edge setting caused very similar sensitivity for both lasers, but with better uniformity of illumination with the pulsed laser.

The absence of the interference rings is due to the relative incoherence of the pulsed laser, compared to the gaseous one. This is primarily due to the quality of the ruby material available at present, as compared to gases. This comparison is intimately related to the comparison of source sizes for the two. The fact that the schlieren sensitivity for both lasers is about the same is because the sensitivity is determined by the angular size of the source image at the knife edge plane. The smallest spot the optical system can form is $4 \times 10^{-3}$ inches, no matter what the source size is. Thus, the sensitivity for both lasers is approximately the same. As mentioned previously, the gas laser source size is estimated at $7.5 \times 10^{-4}$ cm. An upper limit for the ruby laser is established by measurement of craters formed by the focused output of $4 \times 10^{-3}$ inches. These spot sizes help explain the measured results, and allow us to make some estimates relating to system improvements.

The larger source size formed by the pulsed laser does not offer the high inherent sensitivity that the gaseous laser does. However, a source diaphragm of $10^{-3}$ inches diameter can still be used with this system. With an aperture this size a significant amount of the total incident energy is lost at the knife edge. This method is similar to that used with conventional sources, where the source fills a diaphragm, which determines the source size. This spot size is approaching the diffraction-limited spot size for the optics used. The sensitivity which could be realized is not attainable with the present optical system because the smallest source image which can be obtained is about $4 \times 10^{-3}$ inches in diameter. In order to realize the ultimate potential of the ruby laser, this should be reduced by a factor of six or eight, which is approaching the diffraction limit of $4 \times 10^{-4}$ inches. The sensitivity of the present system can be improved by a factor of five with the use of a better optical system.

The system has been positioned at the tunnel. Present physical requirements dictate leaving a 6-foot long free air space between the collimator tube window and the tunnel window, and a much shorter opening on the mirror side. The expedient vibration mounts raise the centerline of the optical system above that of the tunnel, so part of the model is obscured.

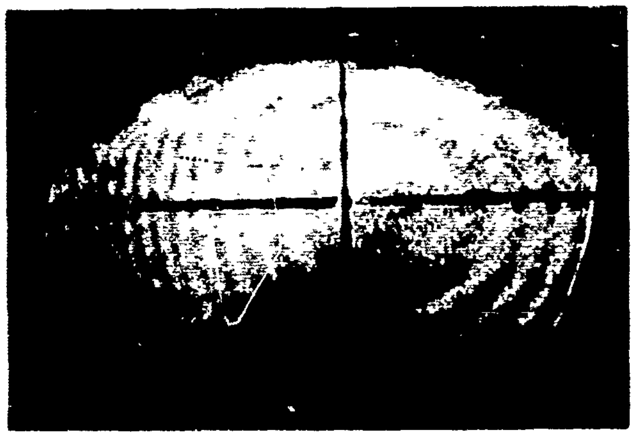


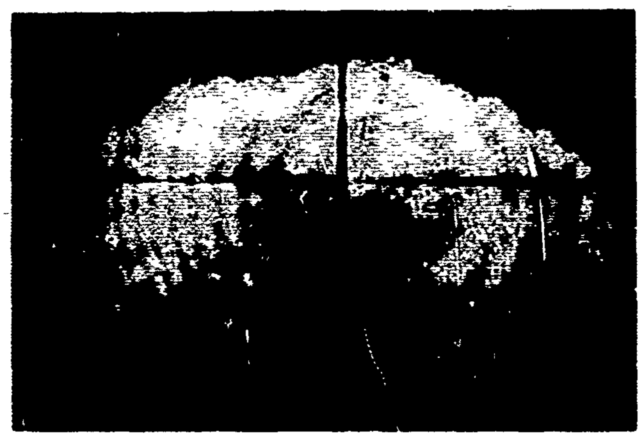
Using Gas Laser Source

Figure 17. Convection Currents Produced by Heated Resistor

Observation through the system, aligned on the tunnel, showed two very noticeable phenomena. The mechanism to eliminate reflections from the beam splitter, also makes the system polarization-sensitive. Such a system shows strains in optically transparent materials as intensity changes. A dark area was observed toward one point around the periphery of the tunnel window. This is attributed to a stress point where the glass is mounted. This can probably be eliminated by releasing pressure on the mounting at the point in question. Another effect is a thin rim of darkening around the tunnel window periphery due to the temperature differential and still air space formed where the window meets the metal frame. Other than these points, the quality of the output image is not significantly worse than those obtained without the tunnel. The gas laser photographs shown in figure 18 were taken with this arrangement, with the tunnel in flow. This was done on the last day at ARL. The lower boundary in these photographs is the upper surface of a conical model. The upper boundary is the edge of the tunnel window. There is quite a bit of structure because of interference effects (possibly more than in previous pictures) due to the additional windows through which the light had to pass. The principal shock wave is easily seen, but a great amount of structure is not visible due to the flow. The main blower in the laboratory was turned off during the run, but the combined environmental factors, such as convection and vibration, took their toll. An attempt was made on this occasion to take photographs using the ruby laser. Camera synchronization was apparently intermittent, and the attempt failed. Operation of the schlieren system and ruby source was observed through the camera viewing port, however.

The other photographs taken on previous occasions with the ruby laser (and a different camera) indicate the improvement in picture quality over those taken with the gas laser source. The same improvement is expected in tunnel conditions.





Top of conical model is at bottom of photograph. The flow is right to left at Mach 14. Two angles of attack are shown. The ring structure is due to interference at windows. The dark area at the lower left is due to stress in a window. The dark boundary at the top is either stress or temperature differential where the window meets the tunnel structure. The pictures were taken through a free air path of approximately six feet with the Gas Laser Source.

Figure 18. First Photographs on Operating Tunnel

## III. CONCLUSIONS AND RECOMMENDATIONS

The work on this contract involved the development of a pulsed-laser source with less than 0.1 microsecond pulse duration, the combining of this and a cw laser into a laser source, and the incorporation of this source into the existing schlieren optical system at ARL.

The contractual work has been accomplished and is documented in this report. The demonstration of the high sensitivity inherent in the laser sources has been frustrated by certain practical difficulties. The work performed has been useful, not only because of the laser source produced, but because it has pointed out problems related to the incorporation of such a source into the conventional system. The information is valuable because this type of system has never been put together before. It has thus served as a practical study of the problems associated with using different types of lasers in schlieren systems, and although the present system is not the ultimate in sensitivity, it may be of sufficient quality for the purposes of the Fluid Dynamics Laboratory at this time.

The evaluation of the laser source was directed toward satisfying the contract specification. It is recommended that the evaluation be carried on from this point. The principal datum of importance is photographs with the pulsed laser of actual tunnel flow in conjunction with normal model testing.

The integrated laser-schlieren instrumentation can be improved and made very useful by consideration of the following:

1. Change in the optical system geometry to an on-axis system.

2. Highly corrected aspheric lens (or parabolic reflector).

3. Vibration isolation designed to the tunnel and floor vibration profile.

4. Temperature isolation, or induced thermal lag, of the composite structure from the laboratory environment.

## APPENDIX

## ALIGNMENT PROCEDURE

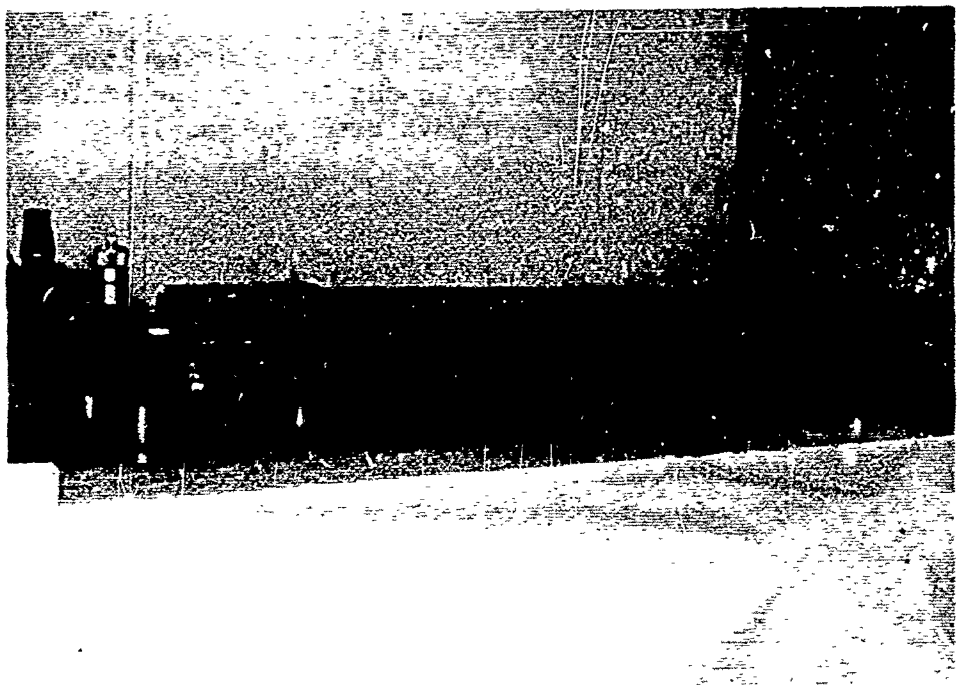
The alignment procedure detailed below is the procedure for aligning the entire system (figure 19). In most instances, only small segments of this procedure need be carried out.

(a) Remove the source aperture and microscope objective. Orient the aluminized mirror and dichroic mirror to send collimated gas laser beam through the center of the microscope objective mount and the beam splitter. Lock the mirrors down. Adjust the entire source platform relative to the large collimator tube so the beam strikes the center of the spherical mirror. This can be done best by peering into the large window at the end of the tube and observing the beam on the mirror. Adjust the large external plane mirror to return the beam as closely as possible to the center of the spherical mirror. At this point, it is ususally possible, if the knife edge is moved out of the way, to see the returning light in the camera viewer.

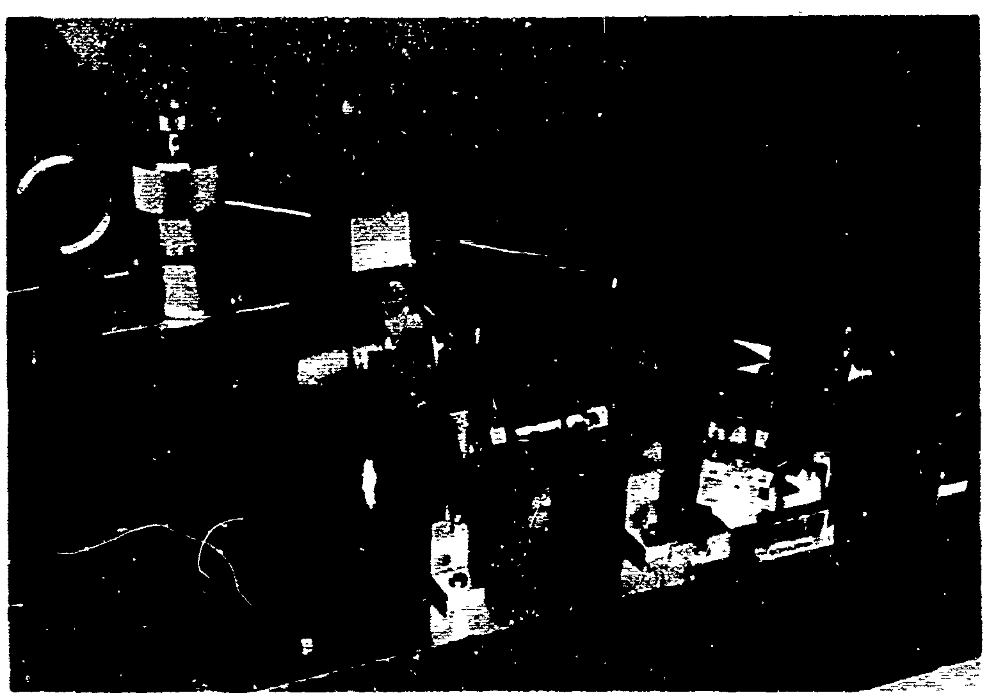
(b) The next step is to insert the microscope objective in its mount and position it longitudinally so that it focuses the laser beam at the focal point of the spherical mirror. This position is best determined by comparing the outgoing and returning light and seeing that they focus at the same point, i.e., the source object distance and image distance should be the same. The test chamber should then be visible in the camera viewer, but will not be aligned exactly, as evidenced by the two visible sets of cross hairs. Bring these into coincidence by using the remote adjustments on the large external plane mirror. If the test chamber is not visible in the laser, the knife edge is probably in the way and this should be cranked out of the way.

(c) Insert the source diaphragm, or aperture, in its mount. If it does not transmit the beam, adjust to its proper position at the focus of the microscope objective. The first step in this process is to loosen its mounting screws slightly so that the mount may be slid on the aluminum plate. Move the mount away from the microscope objective and adjust it laterally until a small spot of light with circular symmetry is transmitted through the aperture. Place a piece of masking tape over the back of the aperture mount to act as a screen and facilitate this adjustment. Slowly move the aperture block toward the microscope objective, making small adjustments in the mount (using special wrench for this purpose) to keep the observed spot properly positioned vertically. When the proper position is reached, the small spot balloons into a wide bright spot. When this occurs, the proper longitudinal position has been reached. Tighten down the base screws. Make small final adjustments in the mount to optimize the transmitted light distribution. The placement of this aperture should improve the evenness of the illumination in the test chamber.

(d) Coarse-position the knife edge so the flexure movement is able to completely cutoff and completely pass the light beam without putting undue stress on the movement. To perform the horizontal lateral adjustments, loosen the four knurled screws beneath the aluminum plate. To perform the vertical adjustment, loosen the four screws on the collimator tube side of the knife edge assembly and displace this plate up or down to the proper position. Crank the micrometer out of the way for this adjustment. Note that the cross hairs should be aligned as exactly as possible before coarse adjustment of the knife edge is performed, because a small



(a) Composite Laser source and camera



(b) Optical platform

Figure 19. Laser Sources for Aerospace Research Laboratories' Schlieren System

adjustment of the plane mirror (used to bring the cross hairs into register) corresponds to a relatively large motion of the output spot at the knife edge plane. These adjustments suffice to do schlieren work with the gas laser. The next step is to align the ruby laser with the system.

(e) Several auxiliary components are incorporated into the system to facilitate the alignment of the ruby laser. These are the laser mounting itself, the gimbaled glass flat, the alignment mirror mounted outboard of the beam splitter, and a viewing screen of opal glass to the left of the knife edge assembly. First, remove the microscope objective and source aperture, using the quick change feature of these mounts. This feature enables the removal and replacement of these components without misalignment. Adjust the small alignment mirror so the gas laser light is reflected back into the end of the laser. When it is close, a small secondary spot of light will appear on the opal viewing screen near the primary spot. The secondary spot moves as the alignment mirror moves. Position the secondary spot near (but not on) the primary spot. This spot is caused by a reflection off the front of the gas laser cavity.

(f) Uncover the pulsed laser. Locate a faint spot of light, due to the gaseous laser, hitting the front of the pulsed laser. To facilitate this operation, work in a darkened area and hold a small piece of white paper just in front of the laser to act as a screen. Adjust the attenuating prism to make this spot brighter. Align the pulsed laser laterally, using the coarse adjustments (knurled brass knobs in base) so this beam enters the front end of the laser housing. Lock the front adjustment by tightening up the knurled brass knob underneath the platform.

(g) Make angular adjustments of the pulsed laser until a second faint spot which moves as the pulsed laser moves is viewed on the opal glass viewing screen. Make horizontal adjustments by displacing the rear end of the pulsed laser manually, and make vertical adjustments by manipulating the knurled brass knobs at the rear of this cavity.

Align the faint spot with the other faint spot already positioned on the screen. The 10X microscope objective held in the hand can be used to advantage in the exact alignment of these two spots. Take care not to apply pressure to the mounting platform or gas laser base when making these adjustments because the alignment will change when such pressure is released. Once this alignment is accomplished, tighten the lock on the pulsed laser base (underneath the chassis). This procedure aligns the two lasers angularly. Replace the microscope objective and aperture.

(h) Fire pulsed laser with the camera sync disconnected to enable the operator to view the pulsed picture. If the test chamber is not evenly illuminated, cock the gimbal-mounted glass in front of the laser to cause even illumination of the test chamber. The angle adjustments and the translational adjustment are independent. When this is done, carefully replace the pulsed laser cover. If no illumination is visible when the laser is fired, crank the knife edge well out of the way, and if no positive results are obtained yet, repeat steps (f) and (g) above. When this step is completed the system is ready to take photographs, using either laser. Operating instructions for this are included in the Operation Manual.

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## DOCUMENT CONTROL DATA - R&D

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| | Aerospace Research Laboratories (ARF)<br>Office of Aerospace Research, USAF<br>Wright-Patterson Air Force Base, Ohio |

13. ABSTRACT
The purpose of the present contract was to develop and produce a laser source for the 10 inch schlieren system presently in use at the Fluid Dynamics Laboratory of ARL. The source, which uses a He-Ne Gas Laser for continuous viewing in conjunction with a Q-switched ruby source for taking very short exposure time photographs, has been developed and incorporated into the existing system. Certain problems still exist which greatly limit the overall system performance, but these are due to factors such as vibration, temperature fluctuations, and the quality of the existing optical system. Recommendations are made for the development of an overall system which will allow the potential of the laser source to be realized.

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Security Classification

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